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Is functional integration of resting state brain networks an unspecific biomarker for working memory performance?

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ABSTRACT

Is there one optimal topology of functional brain networks at rest from which our cognitive performance would profit? Previous studies suggest that functional integration of resting state brain networks is an important biomarker for cognitive performance. However, it is still unknown whether higher network integration is an unspecific predictor for good cognitive performance or, alternatively, whether specific network organization during rest predicts only specific cognitive abilities.

Here, we investigated the relationship between network integration at rest and cognitive performance using two tasks that measured different aspects of working memory; one task assessed visual–spatial and the other numerical working memory. Network clustering, modularity and efficiency were computed to capture network integration on different levels of network organization, and to statistically compare their correlations with the performance in each working memory test.

The results revealed that each working memory aspect profits from a different resting state topology, and the tests showed significantly different correlations with each of the measures of network integration. While higher global network integration and modularity predicted significantly better performance in visual–spatial working memory, both measures showed no significant correlation with numerical working memory performance. In contrast, numerical working memory was superior in subjects with highly clustered brain networks, predominantly in the intraparietal sulcus, a core brain region of the working memory network.

Our findings suggest that a specific balance between local and global functional integration of resting state brain networks facilitates special aspects of cognitive performance. In the context of working memory, while visual–spatial performance is facilitated by globally integrated functional resting state brain networks, numerical working memory profits from increased capacities for local processing, especially in brain regions involved in working memory performance.

Introduction

In recent years, there has been a growing interest to investigate complex brain networks derived from functional connectivity patterns during rest and to relate the organization and topology of these networks to cognitive performance. Although these studies could impressively demonstrate correlations between the topology of resting state networks and cognitive performance, the specificity of these correlations has not been thoroughly investigated. Resting state network topology might affect a broad range of cognitive abilities like the g-factor in intelligence (Colom et al., 2006; Jung and Haier, 2007) or, in contrast, may selectively influence a specific cognitive process. The aim of the present resting state study is to investigate the *specificity of functional network attributes* in relation to working memory performance, and to test whether a certain pattern of network integration, i.e. the potential to combine information processing across different processors or nodes of the brain, during rest selectively facilitates specific aspects of working memory performance.

Network integration can facilitate information processing on different organizational levels of complex brain networks (Fig. 1A). Clustered brain networks, with many neighbouring nodes connected to a specific node, can support local processing; modular networks, with many connections within and only a few connections between functional modules, can promote a network's ability to integrate distributed information on an intermediate scale (Sporns, 2013), and networks with short pathways between their nodes have been shown to support parallel (or global) information processing of the whole system (Latora and Marchiori, 2001; Bullmore and Sporns, 2012).

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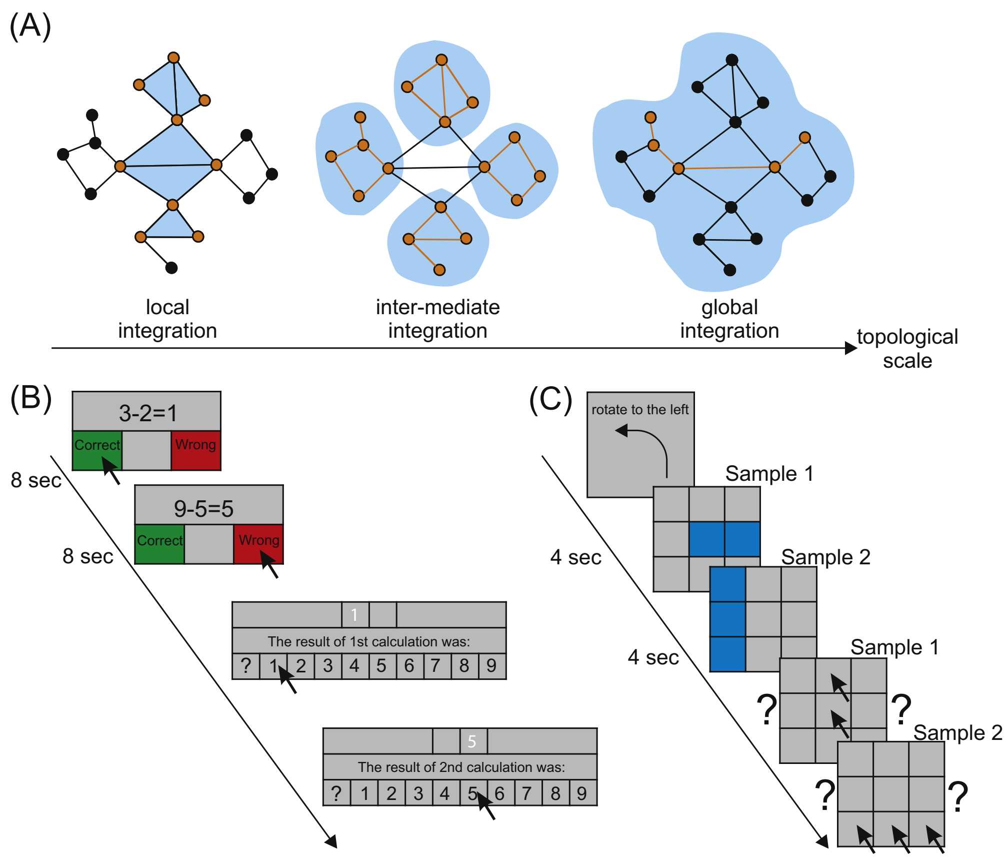

Fig. 1. Illustration of the network attributes of functional integration, and the working memory tasks used in the present study. (A) Network integration can be studied on different organizational levels based on the topological scale at which network attributes are defined. *From left to right*: network clustering, modularity and global efficiency capture information integration on local, inter-mediate and global levels of network organization respectively. Nodes with many connections to their direct interconnected neighbours form local clusters (*left graph, orange nodes*). Dense groups of connected nodes form modules (*middle graph, orange nodes and links*). In a globally efficient network nodes can communicate with each other through short paths (*right graph, orange path*). (B/C) Illustration of both working memory tests. (B) The 'computational span' (CS) test. Participants had to indicate whether the results of simple equations were correct or wrong by clicking on a button. Following the presentation of several equations participants were asked to recall the results in the correct order. (C) The 'spatial working memory' (SWM) test. Participants were instructed to rotate up to three upcoming patterns by 90° to the right or left. The simple spatial patterns were presented one after the other. Participants had to mentally rotate the spatial configuration and remember the resulting pattern. Following these item presentations participants were asked to recall the resulting patterns by clicking on cells within a response grid.

Several studies support the idea that functional network integration on different organizational levels of resting state brain networks facilitates cognitive performance in a wide range of cognitive domains. For example, Kuhnert et al. (2013) found better recall performance in a verbal memory task in subjects with more clustered brain networks. The studies by Li et al. (2009) and Van den Heuvel et al. (2009) showed that the efficiency of brain networks predicts better cognitive performance in IQ tests. Furthermore, Bassett et al. (2009) found a significant correlation between working memory performance and network integration on the whole brain level: in healthy young adults and patients with schizophrenia the efficiency of brain networks significantly correlated with working memory performance. Other studies investigated network integration on an intermediate scale and showed that highly modular networks, with many connections within functional modules and only a few connections between modules, are associated with superior task performance. For example, Stevens et al. (2012) showed that subjects with more modular brain networks performed better in a visual–spatial working memory task. Previous studies conducted in our lab suggest that while network integration on a global level is positively correlated with the performance in sustained attention tasks, local clustering correlates negatively with task performance (Breckel et al., 2013; Giessing et al., 2013). In summary, positive correlations between working memory as well as other 'higher order' cognitive functions on one side and functional integration of complex brain networks on the other side have been found on local, intermediate and global levels of the brain network organization.

In the current study functional resting state networks of 22 participants were analysed and the network attributes *clustering*, *modularity* and *efficiency* were computed to statistically investigate the relation between resting state network integration on different organizational levels and performance in two working memory tests. We used these network diagnostics to investigate how specific network integration is related to the performance in tasks which assess two different aspects of the same cognitive process.

Previous working memory studies have documented that when subjects are asked to process and store visually presented materials, two different cognitive facets can be distinguished depending on the content of the presented information: working memory tasks with numerical or verbal content on one side, and working memory tasks with spatial–figural content on the other side (Oberauer et al., 2000; Süß et al., 2002; Vock and Holling, 2008). The separation of these two content domains of working memory fits with the model of working memory proposed by Baddeley (1986). He suggested that visually presented stimuli with verbal labels (like words or numbers), if phonologically coded (Henry, 2012, chapter one, page 7), are stored and rehearsed in an articulatory loop, whereas spatial and pictorial materials are processed and memorized in a different slave system (Baddeley, 2012; see Smith and Jonides, 1997, for a more fine-grained distinction between working